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FSCBG Model Input Sensitivity Study

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Summary

This paper summarizes a complete sensitivity study of all input variables into the FSCBG Version 4.0 computer model, including the near-wake AGDISP representation, helicopter and fixed-wing aircraft, and drop size distribution. A linear analysis is performed around a nominal, or base case, parameter set. Trends in the results may be explained, for the most part, on a physical basis; however, the worth of the present analysis is its quantification of the relative sensitivity of the results to known input variable changes. The importance of these variations are catalogued relative to effectiveness of swath width deposition and off-target drift. These results quantify several critical variables regarding aerial application, specifically those variables that must be carefully controlled or monitored during spray operations. In order of importance they include: release height, spraying speed, wind speed, and wind direction.

Introduction

The USDA Forest Service in cooperation with the U. S. Army has developed the Forest Service Cramer-Barry-Grim (FSCBG) aerial spray model (Teske et al., 1992) incorporating the Agricultural Dispersal (AGDISP) model (Bilanin et al., 1989). The FSCBG model predicts the transport and behavior of pesticide sprays released from aircraft. The AGDISP near-wake representation solves a Lagrangian set of equations for the position and position variance of material released from each nozzle on the aircraft. The motion of this material is affected principally by the wing or rotor tip vortices, crosswind and evaporation. The FSCBG far-wake representation begins with the results of AGDISP at the top of a defined canopy or near the ground, and solves a Gaussian diffusion equation to recover ground deposition.

The AGDISP model includes simplified models for aircraft wake and ambient turbulence effects including wing-tip vortices, helicopter downwash and forward flight, jet engines and propellers, crosswind, vortex decay and material evaporation. The model tracks the motion of a group of similarly-sized particles or droplets released into the atmosphere from specified nozzle locations. The similarly-sized droplets are combined in a drop-size distribution to generate the spray droplet cloud. The novel feature of the AGDISP model is that the dispersion of the group of similarly-sized droplets resulting from turbulent fluid fluctuations is quantitatively computed within the wake of the aircraft as the group of droplets descends toward the ground. The accuracy with which AGDISP can compute dispersion of this group of droplets is intimately related to specifications of the turbulent fluid fluctuations through which the droplets must pass and the local fluid velocities in the vicinity of the aircraft releasing the material.

FSCBG is a Gaussian line-source model that takes the near-wake results from AGDISP and predicts downwind dispersion including the effects of evaporation, meteorology, canopy penetration, and ground and canopy deposition. FSCBG is a complete-wake model in that it includes an analytic dispersion model for multiple line sources oriented in any direction to the wind, an evaporation model for volatile spray components, a canopy penetration model for forest canopy interception, and the near-wake model AGDISP for initial spray source distribution. A review of the technical aspects of the FSCBG model may be found in Teske (1992) and Teske et al. (1992).

The model is directed toward a complete prediction of the behavior of the spray material after it is released from the nozzles. Drop size distributions give the mass distribution of material as it is atomized by the nozzle. Drops containing volatile materials (such as water) begin to evaporate immediately upon entering the atmosphere, with the local temperature and relative humidity determining the rate of evaporation. The presence of the aircraft wake (with its vortical structure) may move material to unanticipated locations. Ambient winds superimpose additional horizontal velocity vectors on the spray material. Canopy deposition strips spray material and prevents nonvolatile components from reaching the ground. Every aspect of the spray process is affected by the size and significance of atmospheric and aircraft-generated turbulence.

Meteorological calculations generate the background wind speed, temperature and relative humidity profiles. Evaporation calculations track the time rate of decrease of drop size of drops that are released into this background. Canopy calculations remove additional material through impact on vegetation. Near-wake calculations follow the behavior of released spray near the aircraft, and when out of wake influence or at the top

of the canopy, hand off to the dispersion calculations to predict the dosage, concentration and deposition at user-designated locations.

Both models have recently been compared against field data (Bilanin et al., 1989, Teske et al., 1991b, and Barry et al., 1992). The next logical step is to explore the sensitivity of input variables entered into these models. A preliminary sensitivity study appears in Teske et al. (1991a).

At this point many options become available, depending on the aircraft type chosen and the goals of the study. Ideally, two aircraft (fixed-wing and helicopter) would be studied, systematically varying every input parameter and obtaining extensive predicted results that could be appropriately nondimensionalized to collapse the data. To this end the following assumptions have been applied to this study:

1. The USDA Forest Service typically uses the Bell JetRanger III helicopter and the Ayres Turbo Thrush fixed-wing aircraft for their gypsy moth spraying. By default these two aircraft become the base case aircraft considered here. The effects of jet engine and biplane wing sensitivity are modeled by artificially adding these features to the Ayres Turbo Thrush. Default aircraft characteristics are obtained from the FSCBG aircraft library (Hardy, 1987).

2. When combating the gypsy moth, the USDA Forest Service typically uses biopesticides such as Foray 48B undiluted (*Bacillus thuringiensis*) as a spray material. By default this spray material becomes the base case material sprayed in the sensitivity study (evaporation and downwind drift sensitivity are further explored by spraying water). Drop size distributions are obtained from the FSCBG drop size library (Skyler and Barry, 1991).

3. When using the base case aircraft, the USDA Forest Service typically positions four Beecomist 360A rotary nozzles on the Bell JetRanger III, and six Micronair AU5000 rotary nozzles on the Ayres Turbo Thrush. These configurations become the base case nozzle types and number, although further sensitivity is explored with 8004 flat fan nozzles to generate a full-boom deposition pattern. Defaults place nozzles across no further than 75 percent of the wing span or rotor diameter.

4. Canopy sensitivity effects are obtained by adding the Heather Seed Orchard canopy characteristics when needed (Teske et al., 1991b). The recent FSCBG model addition for the LiCor instrument is not explored.

5. Default meteorological characteristics are assumed typical for spraying in the Northeast for gypsy moth (Teske et al., 1990). Detailed evaporation model inputs are not explored. In all cases meteorology is defined by a single temperature, relative humidity, wind speed, and wind direction through the mixed layer.

6. Nonvolatile deposition on the ground will be the predicted result analyzed. Dosage and concentration have not been extensively validated in the model, although these efforts are ongoing (Barry et al., 1992). A single flight line flown perpendicular to a row of receptors recovers the predicted deposition pattern.

The base case FSCBG input parameter set is given in Table 1 (these parameters are explained more fully in Teske et al., 1992). The applicable drop size distribution data sets are given in Table 2 and plotted in figure 1. Over 400 FSCBG model calculations were performed for this sensitivity study.

Table 1. Base Case Sensitivity Parameter Set

Aircraft Characteristics		
Aircraft Type	Bell JetRanger III	Ayres Turbo Thrush
Weight (kg)	989.3	2745.5
Rotor Diameter or Wing Span (m)	10.17	13.54
Planform Area (sq m)		28.16
Drag Coefficient		0.1
Propeller Radius (m)		1.296
Propeller Efficiency		0.8
Blade RPM	384.0	2000.0
Spray Characteristics		
Spray Material	Foray 48B undiluted	Foray 48B undiluted
Specific Gravity	1.0	1.0
Volatile Fraction	0.15	0.15
Spraying Speed (mph)	60.0	110.0
Relative Height (ft)	50.0	50.0
Nozzle Type	Beecomist 360A (4)	Micronair AU5000 (6)
Emission Rate (gal/min)	5.0	5.0
Meteorological Conditions		
Vortex Decay Coefficient (m/s)	0.56	0.56
Pressure (mb)	1013.0	1013.0
Net Radiation Index	1.0	1.0
Temperature (deg F)	60.0	60.0
Relative Humidity (percent)	65.0	65.0
Crosswind Speed (mph)	3.0	3.0
Canopy Characteristics		
Canopy Height (m)	15.0	15.0
Stand Density (stems/acre)	25.0	25.0
Penetration Probability	0.38	0.38
Vegetative Element Size (cm)	3.0	3.0
Other Characteristics		
Jet Thrust (kg)		3264.0
Jet Radius (m)		1.296
Biplane Wing Separation (m)		1.0

Table 2. Drop Size Distribution Data Sets

Drop Size µm	Mass Fractions: Beecomist 360A Foray 48B undiluted	Micronair AU5000 Foray 48B undiluted	8004 Foray 48B undiluted	8004 Water
45.88	0.0058	0.1320	0.0064	0.0117
73.73	0.0151	0.2607	0.0110	0.0242
106.35	0.0426	0.3002	0.0299	0.0405
138.62	0.0653	0.1830	0.0471	0.1041
171.03	0.1200	0.0841	0.0479	0.1285
203.42	0.1617	0.0254	0.0449	0.1158
235.88	0.1389	0.0092	0.0480	0.1092
268.32	0.1350	0.0038	0.0498	0.1352
301.32	0.0981	0.0013	0.0595	0.1224
334.77	0.0611	0.0003	0.0658	0.0824
366.72	0.0369		0.0858	0.0562
398.21	0.0297		0.1041	0.0282
430.71	0.0250		0.1237	0.0189
463.18	0.0190		0.1167	0.0160
495.68	0.0167		0.0828	0.0033
528.67	0.0108		0.0369	0.0023
Total	0.9817	1.0000	0.9603	0.9989
VMD (µm)	240.2	100.7	383.2	242.2

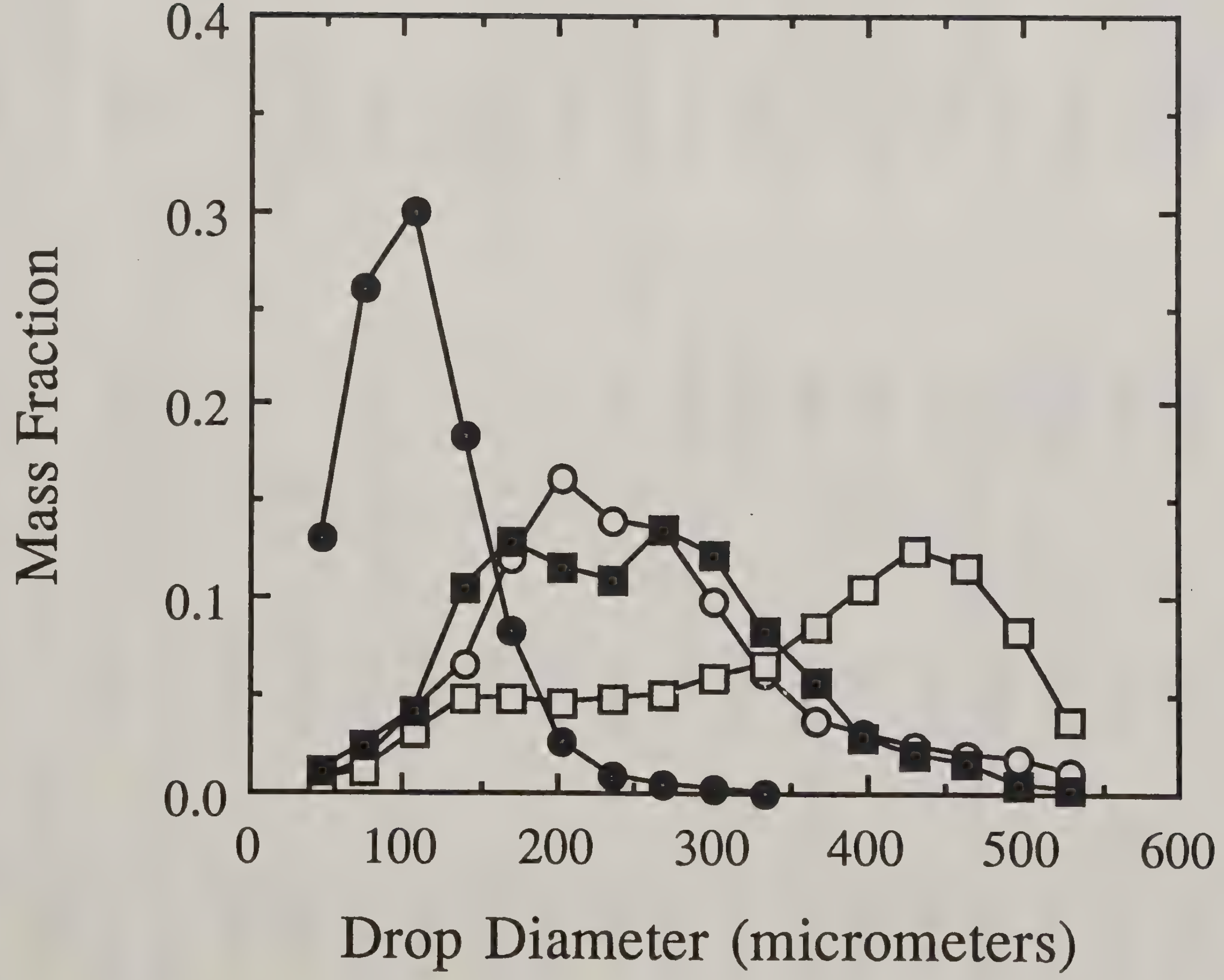

Figure 1. Drop size distribution data sets for the sensitivity study: Beecomist 360A rotary nozzle spraying Foray 48B undiluted (open circles); Micronair AU5000 rotary nozzle spraying Foray 48B undiluted (closed circles); 8004 flat fan nozzles spraying Foray 48B undiluted (open squares); and 8004 flat fan nozzles spraying water (closed squares).

Approach

Sensitivity is explored by evaluating the shape and location of the nonvolatile ground deposition pattern referenced to a base case result. Part of the difficulty in such a complex undertaking is that the results will to some extent become a function of the base case conditions chosen. Unfortunately, no convenient way could be found to get around this difficulty; the best that could be done was to develop a consistent base case configuration. This dilemma should not, however, detract from the results of this study and their implications into the accuracy needed for specific inputs to the model.

Sensitivity is computed with linear changes in the base case conditions. Statisticians would probably agree that more sophisticated approaches could be employed, but these methods would detract from the real intent of this study: namely, generating the importance of input variable accuracy.

In this approach a single variable is changed from its base case conditions, and the effects of this change on deposition profile shape and downwind drift location are evaluated. The two variables of interest are the following:

Figure of Merit. A correlation may be computed for each sensitivity variation and its comparison with the base case, then equated to an algebraic representation:

$$\frac{\mathrm{FOM}}{1+\mathrm{FOM}^2} = \frac{\int c_b \, c_s \, dy}{\int \left(c_b^2 + c_s^2 \right) dy} \tag{1}$$

where $c_b(y)$ is the appropriate base case nonvolatile deposition pattern; $c_s(y)$ is the sensitivity variation nonvolatile deposition pattern; and y is the horizontal downwind distance (measured relative to the centerline of the aircraft). This definition of Figure of Merit is improved over a previous definition (Teske et al., 1991a) to permit the resulting calculations to be more directionally independent, and to reflect the true change between the two deposition patterns. Whether c_b or c_s is the base case condition, the same value of FOM will be computed when employing equation 1 to interpret FSCBG results, along with the restriction that $\mathrm{FOM} < 1$.

If the sensitivity variation gives exactly the same deposition pattern as the base case, the Figure of Merit will equal unity. If c_s is always one-half of c_b everywhere, or twice c_b everywhere, FOM then equals 0.5 . Thus it may be seen that FOM reflects the percentage difference in the nonvolatile deposition pattern from the two deposition patterns. If an acceptable criterion is a ten percent variation in pattern shape, then FOM may reasonably vary from 0.9 to 1.0 in the sensitivity.

Mean Horizontal Position. The nonvolatile ground deposition pattern may be examined to recover the volume-averaged mean horizontal position, measured downwind relative to the aircraft centerline. Nondimensionalization is achieved by dividing the result by the mean horizontal position of the base case to recover the Mean Horizontal Position MHP. This variable then gives an indication of the drift of the material with the

sensitivity. If an acceptable criterion is a ten percent variation in mean deposition location, then MHP may reasonably vary from 0.9 to 1.1 in the sensitivity.

Comparing variable sensitivities among themselves requires formulating a convenient nondimensional number. If a base case variable (from Table 1) is designated V_b, and the sensitivity examines the variable with a value of V_s, it seems clear that the Figure of Merit leads to a nondimensional number of the form:

$$\text{FOM Factor} = \frac{\text{FOM} - 1}{V_s / V_b - 1} \tag{2}$$

It may be seen from equation 2 that when a ten percent increase in V_b to V_s recovers a FOM = 0.9 , the FOM Factor = 1.0 . This factor will then directly interpret all sensitivities in the present study.

The Mean Horizontal Position may be interpreted similarly to give:

$$\text{Drift Factor} = \frac{\text{MHP} - 1}{V_s / V_b - 1} \tag{3}$$

It may be seen from equation 3 that when a ten percent increase in V_b to V_s recovers a MHP = 1.1 , the Drift Factor = 1.0 . This factor will then also directly interpret all sensitivities in the present study.

Sensitivity Results

The principal results of this study are the ordering of sensitivities displayed in Table 3. All controllable inputs into FSCBG were examined by running the Bell JetRanger III and the Ayres Turbo Thrush with both the appropriate rotary atomizers, and with nineteen 8004 flat fan nozzles positioned across 75 percent of the rotor diameter or wing span. Each variable sensitivity involved increasing the variable input above the base case value displayed in Table 1, and decreasing the variable input below the same base case value. The (typically) eight FOM Factors computed (Beecomists on the JetRanger, Micronairs on the Thrush; 8004s on both aircraft; with plus and minus differences) were then averaged to produce the Average FOM Factors displayed in Table 3. The (typically) eight Drift Factors were treated similarly. The larger of these numbers represent the Maximum Overall Factors with which the table ranking was established.

The worth of Table 3 is that, even though these numbers suggest the accuracy of all FSCBG model predictions based on each input variable, these numbers may also be used to infer the accuracy needed to maintain conditions during an actual spray mission.

The numbers in Table 3 may be interpreted most clearly by example. If the wing span of the aircraft is known, for instance, to within only 10 percent of its actual value (an unlikely event), the deposition pattern will be predicted by FSCBG to within only 31.85 percent of what FSCBG would predict if the wing span were entered correctly (10 times 3.185 from the third column of numbers in Table 3). This scale-up effect is why the value of wing span is the most important entry into FSCBG (because the wing span positions the wing tip vortices in the wake of the aircraft).

Typically, every entry into the model should result in no worse than a 1 percent effect on the deposition profile (mutual effects from several input errors have not been explored here). This criterion would suggest that the wing span should be known to within 0.3 percent of its actual value (1 divided by 3.185). Since the wing span can be measured precisely, this level of accuracy should not be a problem.

However, other variables in Table 3 may not be as fortunate. Specific gravity, release height, spraying speed, barometric pressure, wind speed, actual nozzle drop size distribution (reflected in this case through its volume median diameter VMD), and wind direction all require careful meteorological field measurements, or laboratory and wind tunnel studies, to support a 1 percent confidence in the inputs entered into FSCBG, and influencing the deposition in any actual spray mission. Wind speed and direction are particularly important because these parameters are usually evaluated by averaging over a 10-minute data collection time interval. The relative standard deviations from their average values essentially become a measure of the accuracy of these variables.

The variables near the end of the table are significant also, because they are relatively unimportant in deposition and drift.

It may be seen that the actual spray mission parameters of release height, spraying speed, and wind speed and direction strongly influence the deposition and downwind drift of aerially released material. Their actual effects are quantified by the sensitivity factors given in Table 3. To maintain a 1 percent accuracy on deposition pattern and drift effects, for example, requires that the release height be maintained to within 0.5 percent (1 divided by 1.981 from Table 3), spraying speed be maintained to within 0.7

percent, wind speed to within 0.9 percent, and wind direction to within 1.3 percent. Because of atmospheric turbulence, it is doubtful that these field parameters can be maintained to this accuracy. In fact, it is perhaps reasonable to anticipate that the release height and spraying speed will be maintained to within only 5 percent, while the wind speed and direction change by as much as 10 percent in any actual spray mission. These values lead to a 9.9 percent difference from release height variability (5 times 1.981 from Table 3), 7.5 percent from spraying speed, 11.7 percent from wind speed, and 7.7 percent from wind direction; for a combined effect of 36.8 percent. It is no wonder then that significant flight line-to-line deposition patterns result during actual spray missions.

The importance of maintaining tight controls on release height and spraying speed cannot be under emphasized. Traditionally, the USDA Forest Service recommends spraying in the early morning hours, when atmospheric turbulence is fairly quiescent. This is not the case for aerial applications in mid afternoon, when atmospheric turbulence effects are at their peak. Significant variability in deposition patterns will result from not controlling the parameters that influence the deposition and drift behavior. Table 3 summarizes the importance of these parameters.

One note from Table 3 is the relative importance of barometric pressure over temperature and relative humidity. This effect is a manifestation of the evaporation model implemented into FSCBG (Teske, 1992) and may be corrected by defining the virtual temperature, which would have a different variation than for the temperature shown here.

Table 3. Sensitivity Factors Generated by FSCBG Predictions

Variable	Average FOM Factor	Average Drift Factor	Maximum Overall Factor
Wing Span	3.185	1.033	3.185
Nozzles Horizontal	2.429	0.371	2.429
Specific Gravity	2.125	0.805	2.125
Release Height	1.981	1.892	1.981
Canopy Height	1.562	0.152	1.562
Spraying Speed	1.504	0.388	1.504
Barometric Pressure	1.492	0.412	1.492
Rotor Diameter	1.456	0.961	1.456
Wind Speed	1.166	0.981	1.166
VMD	0.771	1.154	1.154
Wind Direction	0.750	0.765	0.765
Aircraft Weight	0.672	0.254	0.672
Tree Envelope Width	0.548	0.053	0.548
Propeller Efficiency	0.460	0.099	0.460
Vortex Decay Coefficient	0.456	0.221	0.456
Nozzles Vertical	0.402	0.201	0.402
Helicopter Blade RPM	0.382	0.275	0.382
Tree Density	0.356	0.048	0.356
Penetration Probability	0.353	0.032	0.353
Biplane Wing Separation	0.341	0.060	0.341

Table 3. Sensitivity Factors Generated by FSCBG Predictions (continued)

Variable	Average FOM Factor	Average Drift Factor	Maximum Overall Factor
Temperature	0.331	0.079	0.331
Propeller Blade RPM	0.318	0.066	0.318
Net Radiation Index	0.298	0.085	0.298
Propeller Radius	0.283	0.078	0.283
Drag Coefficient	0.277	0.057	0.277
Planform Area	0.277	0.057	0.277
Volatile Fraction	0.269	0.056	0.269
Evaporation	0.243	0.085	0.243
Engine Vertical	0.202	0.053	0.202
Engine Forward	0.180	0.011	0.180
Jet Thrust	0.146	0.030	0.146
Relative Humidity	0.141	0.022	0.141
Number of Drop Sizes	0.110	0.036	0.110
Number of Nozzles	0.107	0.016	0.107
Nozzles Forward	0.103	0.044	0.103
Leaf Element Size	0.057	0.025	0.057
Jet Radius	0.047	0.023	0.047

Extended Results

Several variations were examined more closely to determine the effect of larger variability than that obtained from the above sensitivity results alone. These extended results are shown in figures 2 through 6, and include the following:

Figure 2 displays the detailed effect of varying the number of drop size categories computed within FSCBG. The original drop size distribution for the 8004 flat fan nozzle contained 29 drop size categories; its deposition pattern was computed by combining the results of two FSCBG runs. Typically, sixteen drop size categories are used in an FSCBG simulation, although sometimes this number may be reduced by combining adjacent drop size categories further. It may be seen from the figure that the standard practice of maintaining as many drop size categories as possible is a good one, and potentially results in only a four percent difference in deposition, with hardly any difference in drift.

Figure 3 displays the detailed effect of varying the number of nozzles positioned along the spray boom. All numbers above 19 required combining the results of two or more FSCBG runs. It may be seen that the use of fewer than twenty nozzles to represent up to sixty actual nozzles results potentially in a five to six percent difference in deposition, and a three to five percent difference in drift.

Figure 4 displays the detailed effect of varying the atmospheric turbulence structure (wind speed profile shape, mixing height, azimuthal and elevation standard deviations) by varying the FSCBG model input for net radiation index. It may be seen that this parameter may potentially alter the deposition and drift pattern by over ten percent if not entered appropriately.

Figures 5a and 5b display the detailed effects of varying the relative humidity and temperature respectively. It may be seen that a change in ten percent in relative humidity, or ten degrees F in temperature, may cause up to a five percent change in deposition pattern and, more importantly, a ten percent change in drift pattern. Field instruments should, however, be able to measure these two parameters accurately.

Figures 6a and 6b display the detailed effects of varying the crosswind speed and spray release height respectively. It may be seen that these two parameters potentially cause significant changes in the deposition and drift pattern (the scales span more range than in figures 2 to 5). Care must be taken to determine wind speed and aircraft height accurately. These results are consistent with the ranking importance of these two variables in Table 3.

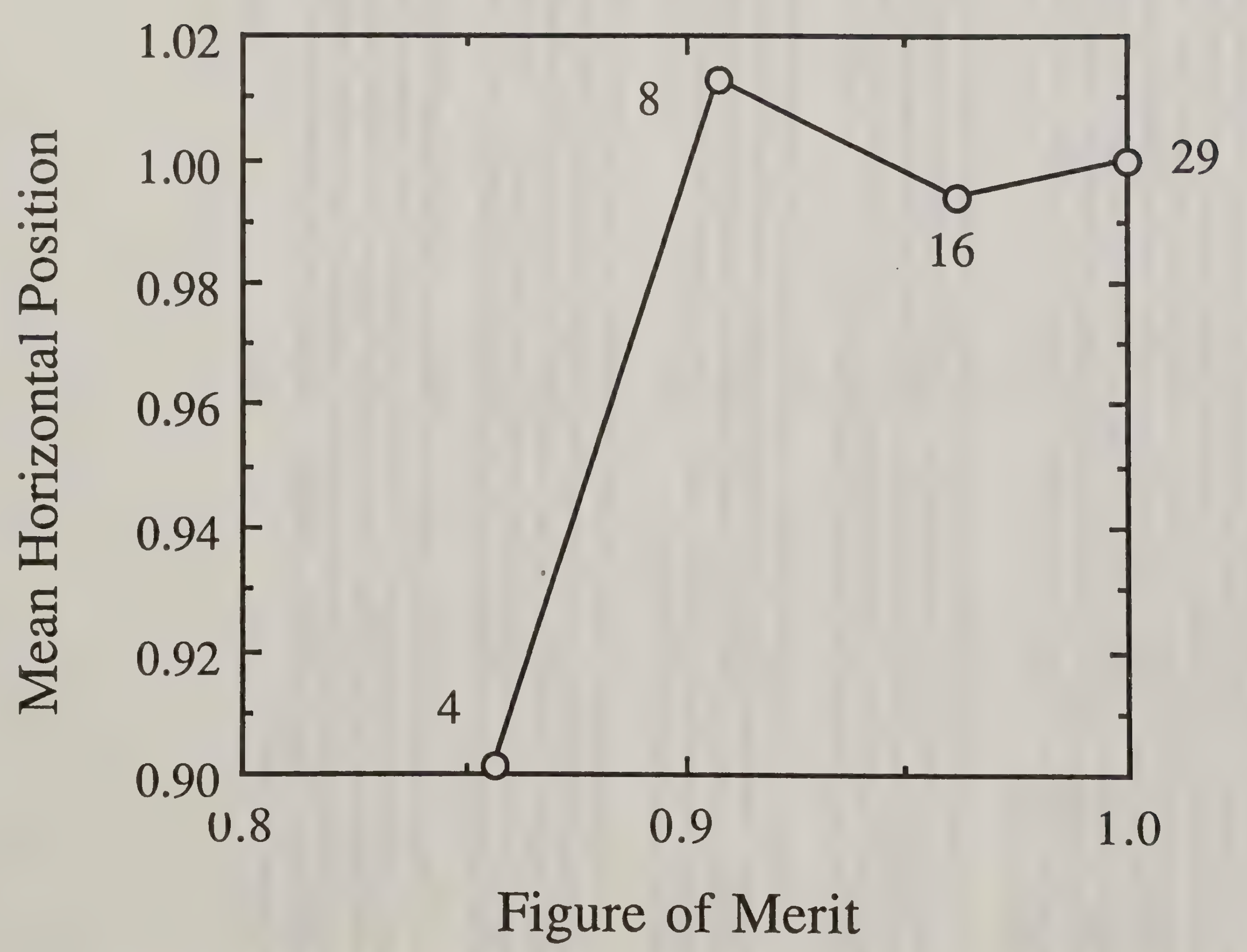

Figure 2. Variation in deposition and downwind drift pattern as a function of the number of drop size categories (indicated on the figure). Predictions performed with an Ayres Turbo Thrush spraying water through 8004 flat fan nozzles.

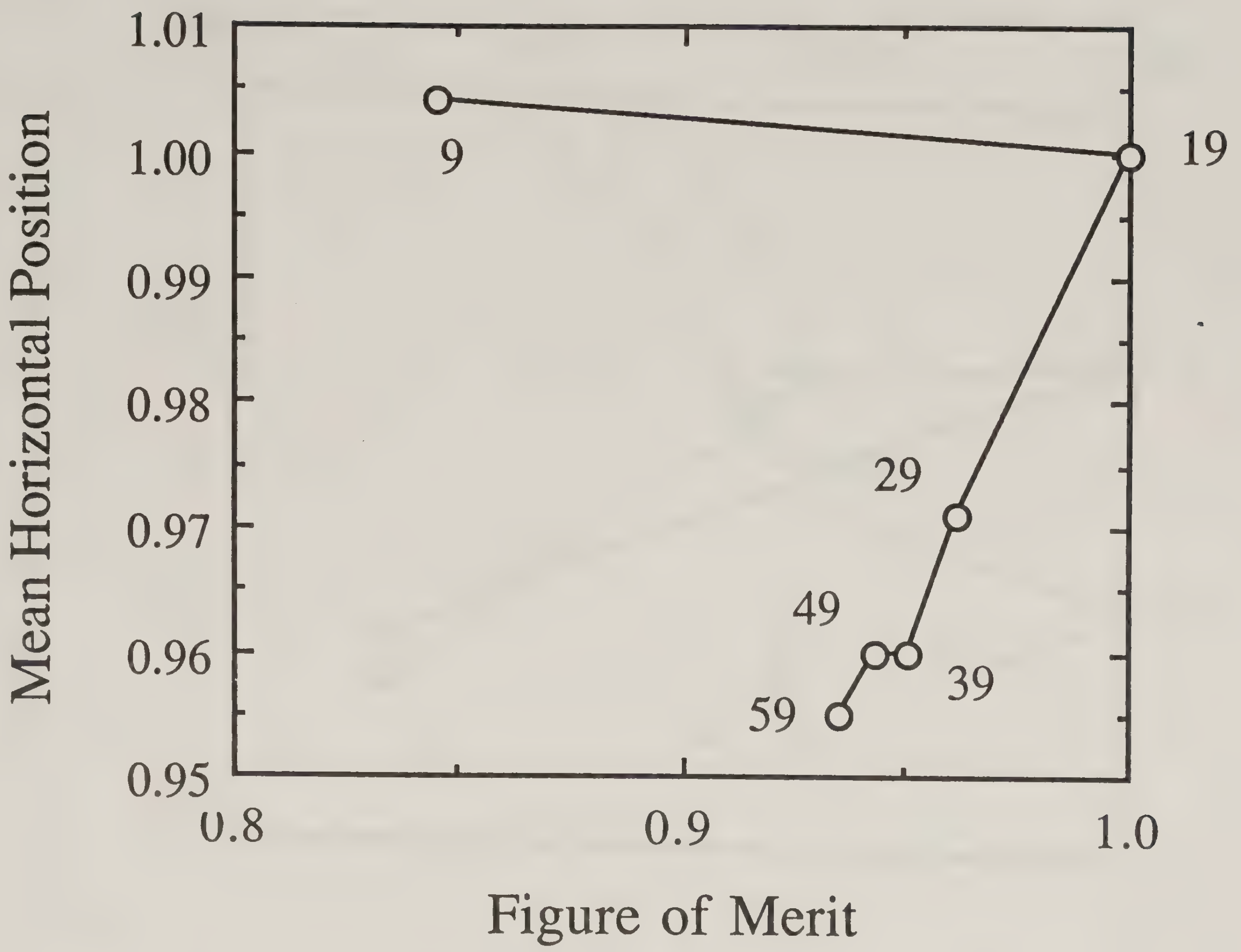

Figure 3. Variation in deposition and downwind drift pattern as a function of the number of spray boom nozzles (indicated on the figure). Predictions performed with an Ayres Turbo Thrush spraying Foray 48B undiluted through 8004 flat fan nozzles.

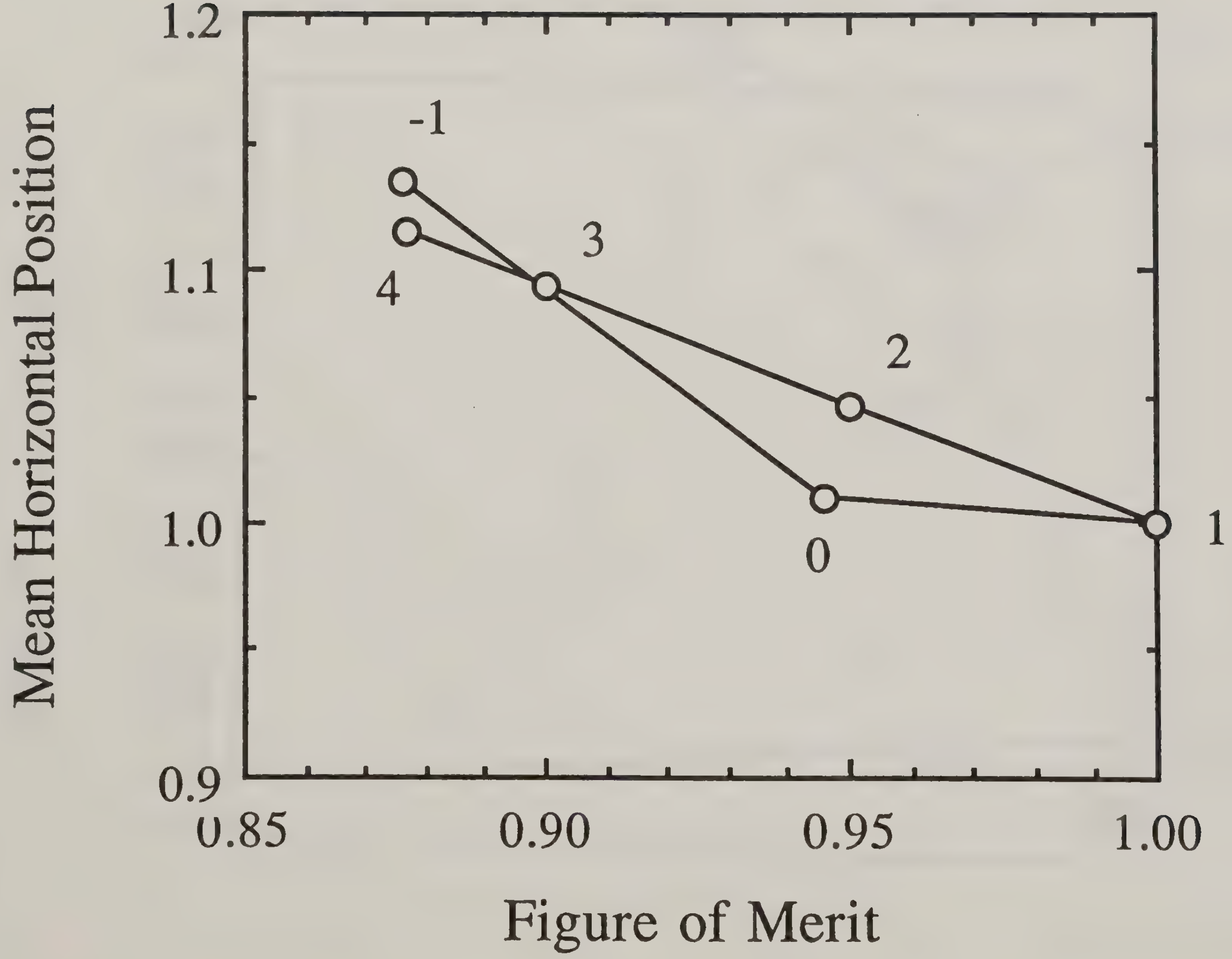

Figure 4. Variation in deposition and downwind drift pattern as a function of atmospheric turbulence level (expressed by net radiation index and indicated on the figure). Predictions performed with an Ayres Turbo Thrush spraying Foray 48B undiluted through 8004 flat fan nozzles.

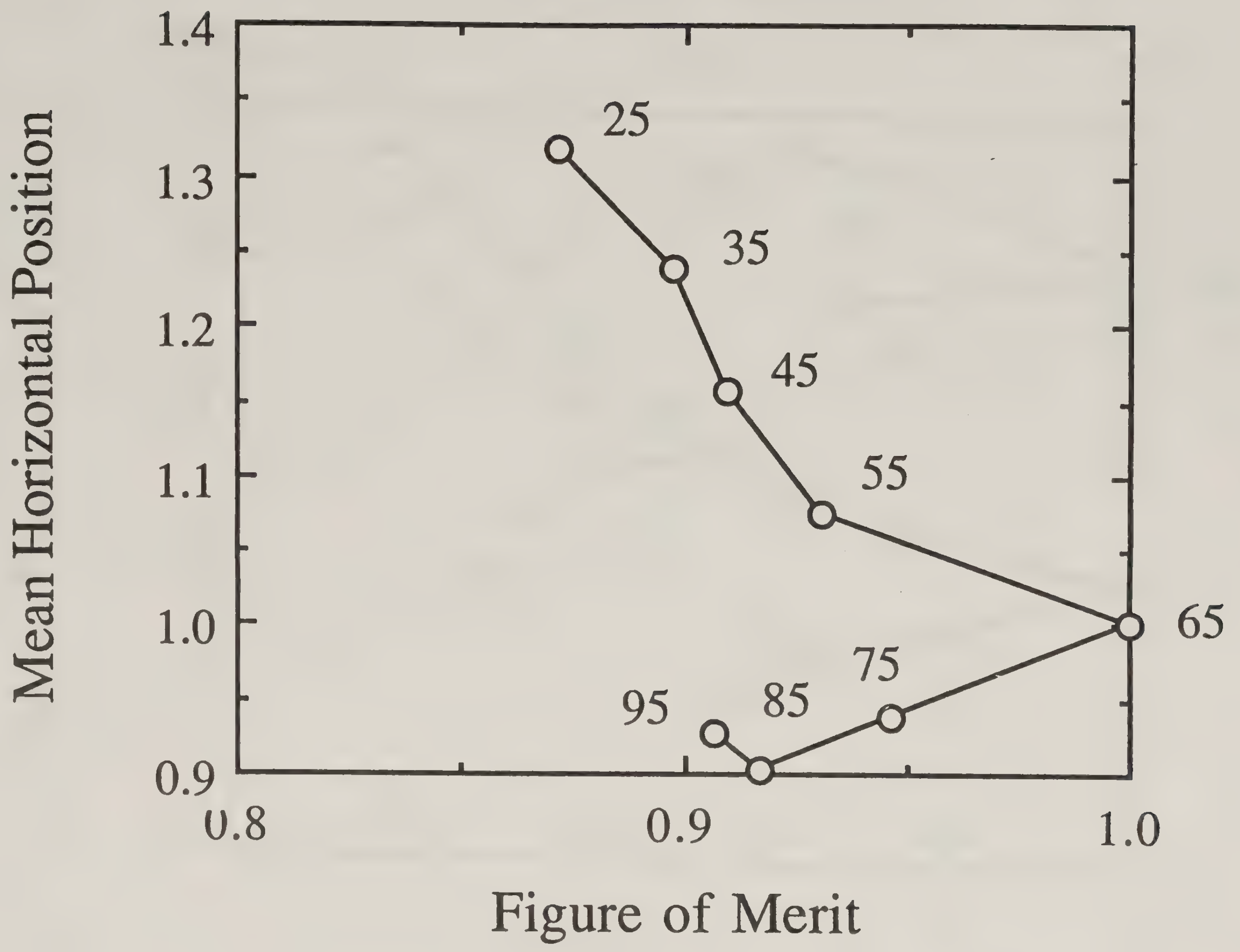

Figure 5a. Variation in deposition and downwind drift pattern as a function of relative humidity (indicated on the figure in percentages). Temperature maintained at 60 deg F. Predictions performed with an Ayres Turbo Thrush spraying water through 8004 flat fan nozzles.

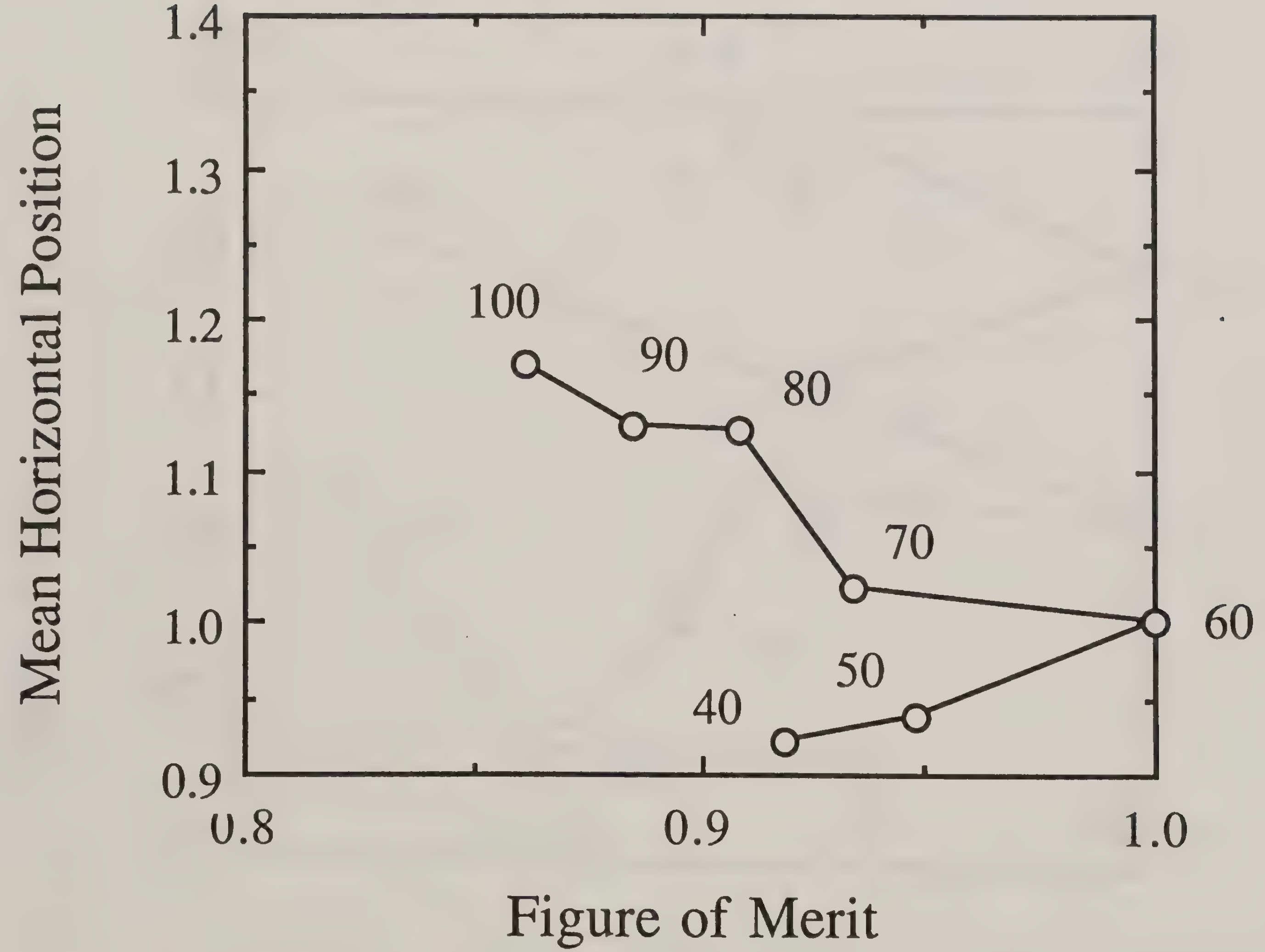

Figure 5b. Variation in deposition and downwind drift pattern as a function of temperature (indicated on the figure in deg F). Relative humidity maintained at 65 percent . Predictions performed with an Ayres Turbo Thrush spraying water through 8004 flat fan nozzles.

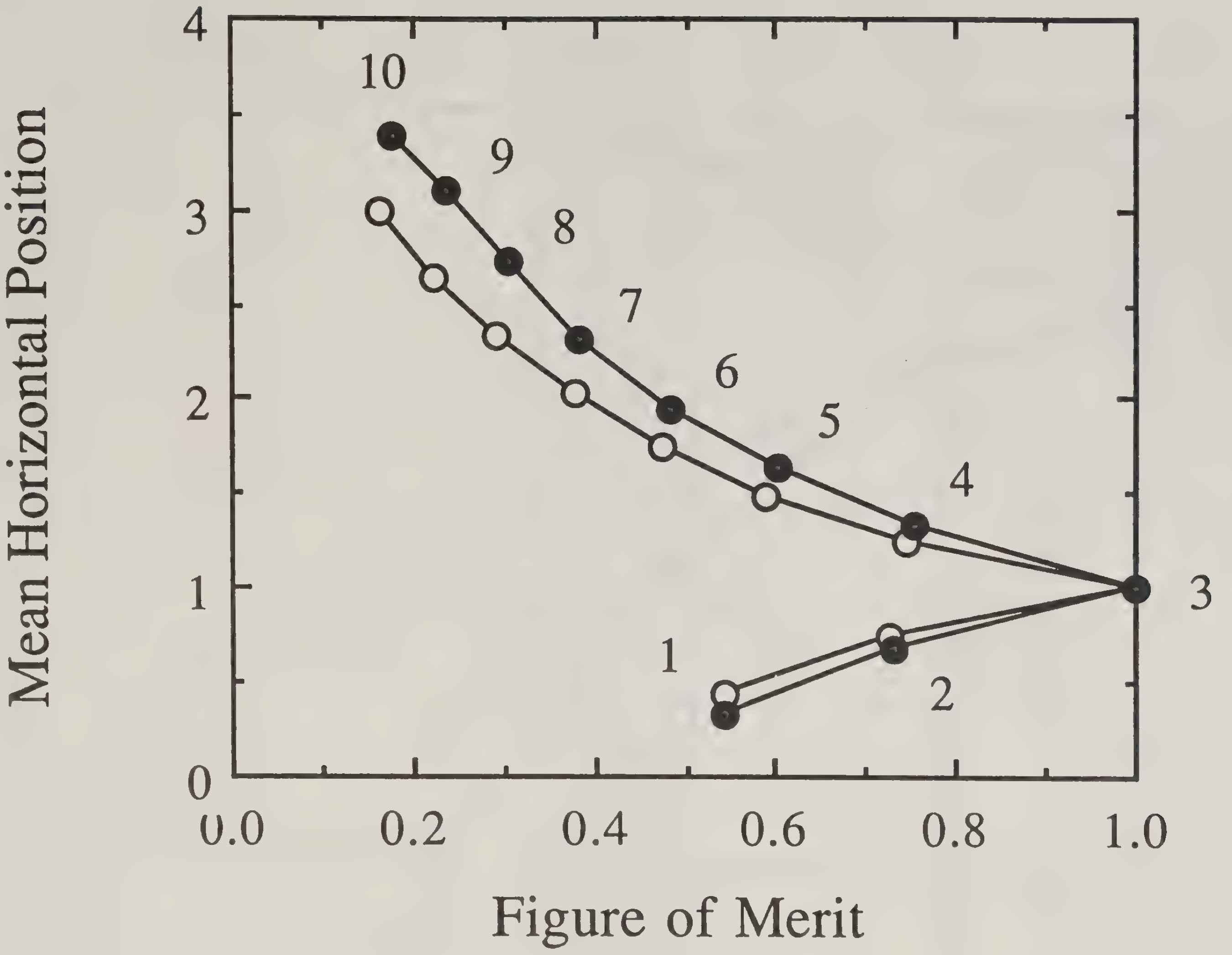

Figure 6a. Variation in deposition and downwind drift pattern as a function of crosswind speed (indicated on the figure in mph). Release height maintained at 50 ft . Predictions performed with an Ayres Turbo Thrush spraying water through 8004 flat fan nozzles: with evaporation (open circles); without evaporation (closed circles).

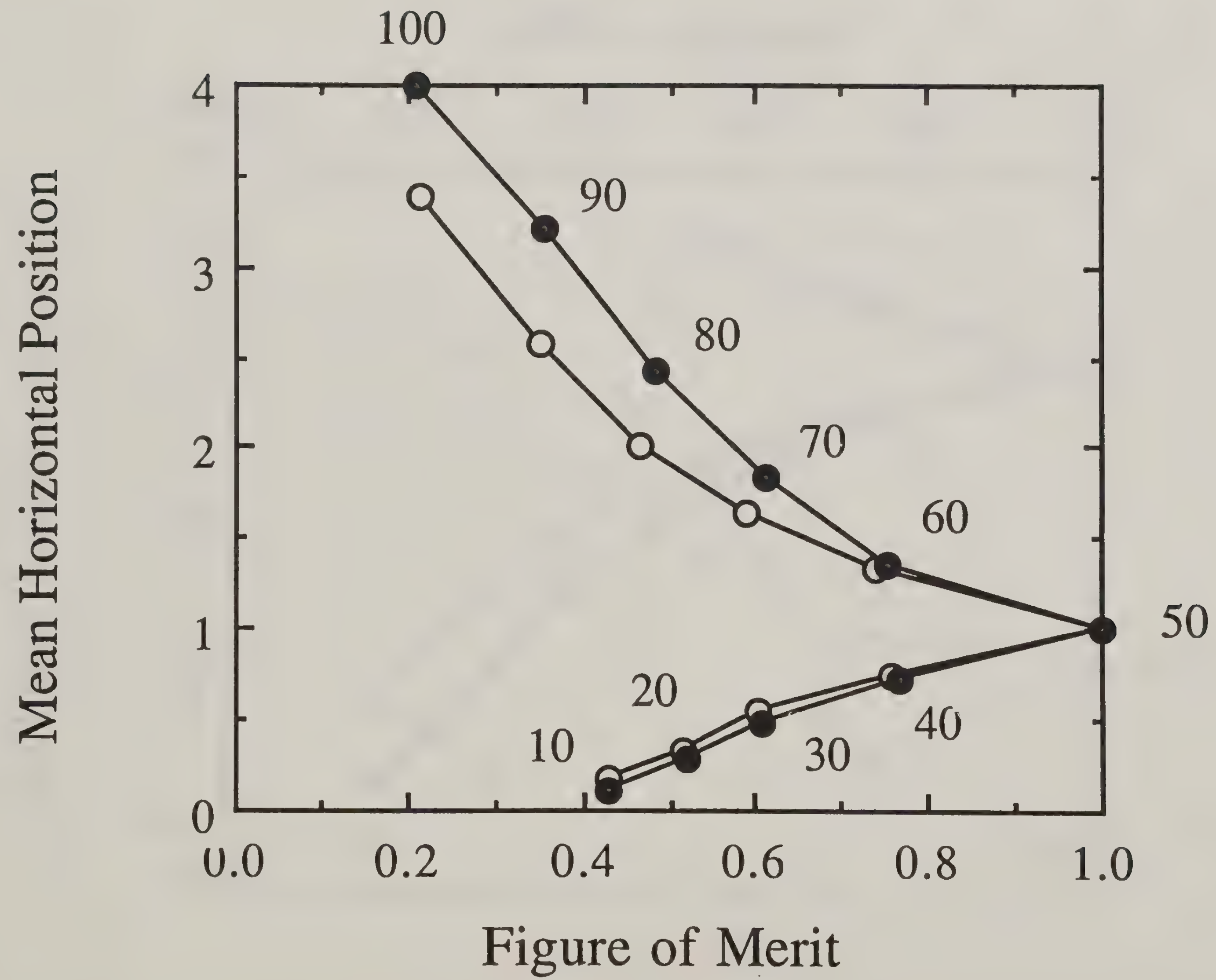

Figure 6b. Variation in deposition and downwind drift pattern as a function of release height (indicated on the figure in ft). Crosswind speed maintained at 3 mph . Predictions performed with an Ayres Turbo Thrush spraying water through 8004 flat fan nozzles: with evaporation (open circles); without evaporation (closed circles).

Conclusions

A detailed sensitivity study of all inputs into the FSCBG aerial spray prediction model finds that the most important variables to maintain are, from most important:

Wing Span
Horizontal Position of the Nozzles
Specific Gravity
Release Height
Canopy Height
Spraying Speed
Barometric Pressure
Rotor Diameter
Wind Speed
Drop Size Distribution Volume Median Diameter
Wind Direction

During an actual spray mission, the variables that should be maintained as carefully as possible are:

Release Height
Spraying Speed
Wind Speed
Wind Direction

The fact that these variables are susceptible to aircraft behavior and atmospheric turbulence suggests that consistent deposition patterns will be difficult to obtain during an actual spray mission, no matter how much care is taken in the field. The relative importance of these variables (summarized in Table 3) should be of use when developing operational spray scenarios, in an effort to concentrate deposition beneath the aircraft and consequently reduce off-target drift and improve efficiency of the spray operation.

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